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Economics and Policy Analysis Series

# The Diffusion of the Use of New Energy Technology as a Context for an Overview of Solar Energy Technologies

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# The Diffusion of the Use of New Energy Technology as a Context for an Overview of Solar Energy Technologies

Alan S. Hirshberg

March 1977

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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# PREFACE

This report is one in a series of reports in JPL's "Economics and Policy Analysis Series". Since the author is no longer with the Jet Propulsion Laboratory, questions regarding this report may be directed to Dr. R. P. O'Toole, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California, 91103.

## ABSTRACT

The process by which new solutions to the energy dilemma are generated and used as a context for an overview of solar energy economics and technologies is summarized in this report.

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# SECTION I

## STAGES IN THE GROWTH OF USE OF ENERGY TECHNOLOGY

To see a World in a grain of sand,
And a Heaven in a wild flower,
Hold Infinity in the palm of your hand,
And Eternity in an hour.

William Blake
Auguries of Innocence

Before any energy conserving process or technology can play a significant role in mitigating the energy dilemma, it must become widely used. In the capitalistic framework of U.S. society, this means that it must achieve commercial use — in short, someone must be able to make money selling it.

Despite the myth of the machine (Reference 1-1), the process by which a new invention is translated into a commercial product not only requires technological development but also social invention (Reference 1-2).

As Wiesner (Reference 1-3) has indicated, many people believe that once technical and economic conditions are met, the innovation will be accepted and diffused rapidly. Unfortunately, the "Better Mousetrap" belief — if you build a better and cheaper gadget, the world will beat a path to your door — is largely a myth. Demonstrating technical and economic feasibility is important, but it is seldom sufficient to insure rapid acceptance and diffusion of a technological innovation, particularly when that innovation does not involve a new service but rather must compete with existing services. Experience indicates that significant resistance often remains after an innovation satisfies requisite technical and economic conditions. Organizational and cultural factors, under some circumstance, impede the acceptance of even feasible, demonstrably cost-saving devices.

Although produced for sale in 1874 and offering large economic advantages (in terms of cost per word), the typewriter was not widely used for over 30 years because of questions about the status of women typists in society and social etiquette. It took more than 350 years and 13 kings to eliminate expensive and inflammable straw from Danish towns. The telephone was resisted not because of technical and economic factors but because it was commonly thought to be "The Work of the Devil;" even Thorstein Veblen denounced it (Reference 1-4). More recently, the Urban Institute has concluded that the inability of cities to utilize cost-saving aerospace technologies can be traced in part to "the traditions of doing things the same old way with the old familiar equipment" (Reference 1-5).

## A. INSTITUTIONAL BARRIERS IN THE HOUSING INDUSTRY

Experience with the housing industry leads to the definition of institutional conditions which, like the technical and economic factors, are capable of deterring the acceptance and diffusion of innovation. These institutional factors have generally deterred innovations, not just solar energy. W. Ewald (Reference 1-6) has estimated that it requires 17 years, on the average, from the invention to the first use of even the most successful innovations in the housing/construction industry. Even innovations promising significant cost-savings have either not been accepted or have required extended time to diffuse. For example, it took 28 years for the industry to widely use forced air heating combined with air conditioning, even though there were major cost-savings to be realized from the combination. According to Ewald, "Changes proceeded piecemeal, in small segments of the industry. There has been no radical change of great technical and economic significance; no single invention or family of inventions."

Donald Schön (Reference 1-7), referring to these institutional factors as "self-reinforcing resistances to change," has demonstrated that most segments of industry possess "fundamentally conservative formal and informal social systems which are aimed at perpetuating things as they are rather than at initiating major changes within the industry" (p. 164). Unfortunately, but understandably, the evidence supports this view.

Institutional factors are composed of at least two principal subfactors: industry organization and industry culture. By organizational factors, I mean the way the industry is set up and operates, including the roles and interrelationships of the various industry members. By cultural factors, I mean attitudes and behaviors that are widely shared among industry members. Of course, these two factors are themselves highly interactive; cultural factors in part arise from the way the industry is organized, and the industry maintains a stable organization because of these cultural factors.

These factors may be viewed as internal survival and response mechanisms used by the industry to cope with its external environment. They reflect "causal contexts" of the environment and produce the somewhat unique industry characteristics (Reference 1-8) which must be understood before developing innovation diffusing strategies.

1. The Innovation/Diffusion Process

The complex process by which an idea is translated into a commercially available and widely accepted product is not well understood. In studying the potential or actual institutional barriers to the widespread use of new solar energy technologies, it is important to distinguish among several stages of evolution along which an idea progresses in the process of being translated into a widely diffused technology. Conceptually the process consists broadly of three distinguishable, overlapping phases: innovation, the diffusion of readiness, and the diffusion of innovation.[1]

[1] There has been a good deal of research on the diffusion of innovations. The model presented here was constructed with the idea of commercial adoption of a technical device. The more general research on the diffusion process identifies the elements in the diffusion process. In Communication of Innovations, Everett Rogers and F. Floyd Shoemaker define the elements as "(1) The innovation (2) which is communicated through certain channels (3) over time (4) among the members of social system" (p. 18). Diffusion of readiness represents that time-dependent process during which the attitudes of industry members are altered by communicating within the industry media.

By innovation I mean the initial, evolutionary stages of an idea, concept or design before it is translated into a commercially available product or process, such as research leading to the development and production of a line of solar collectors.

Included in the innovation phase are two interrelated stages — invention and research. In the former, the new concept is invented. Often this occurs through speculation and can be based on no more than a hunch. In the latter, the underlying principles of the innovation are understood and a theory is developed to explain its workings.

The theory need not be scientifically complete but it must be sufficient to supply an adequate rational model for the operation and development of the invention. Every theory presupposes an underlying paradigm (a set of assumptions, assertions and faiths concerning the world) through which the invention can be viewed and which lead to the technical understanding of the operation of the innovation.

The paradigm is like a filter which provides a means for abstracting both from primary observation of the world and from first-order experience. The result is a description and interpretation of what is going on and leads eventually to a sound theory. This process is described by Bois (Reference 1-9) as the structural differential and the paradigm is a semantic filter which provides (and limits) the abstracting process.

Major inventions often occur when two conflicting paradigms are in collision. This collision begins with the failure of an older paradigm to explain, with adequate rationality, new observations which have produced puzzles to a group of investigators. The result is the birth of a new paradigm through which these new puzzles can be explained. This process produces scientific revolutions and a succeeding discovery of new inventions (Reference 1-10).

A good example of this process of paradigm collision is the discovery of oxygen. At that time the Phlogiston Theory could not adequately explain observations related to the burning of objects such as wood. Because phlogiston was supposedly given off during burning (which was called de-phlogistonization), scientists could not explain the increase in the weight of material after burning. Lavorsier, who is given credit for the discovery of oxygen, presumed a different paradigm (on which modern chemistry is partly based) which supposed burning to be explained as the addition of new material (oxygen) rather than the loss of phlogiston. Although the new theory and underlying paradigm appear elegant and self-obvious, at the time it was revolutionary; so much so that Lavorsier was afraid to present his theory openly to fellow members of the Royal Scientific Society (Reference 1-10).

2. Invention

The invention and research stages often overlap and are interrelated. Invention often comes out of research, and invention leads to new research areas and questions. The innovation phase provides the basic scientific theories and research on which technology and eventually the commercial product are built. It leads to the next phase in the commercial development process — the commercial "readiness" stage.

3. Diffusion of Readiness

Diffusion of readiness refers to the activities which generally precede the economic viability and actual commercial diffusion of a new technology, but which prepare the public and the industry concerned for the diffusion. In the case of solar energy technologies, a program to accept large scale diffusion would include workshops and information exchanges and labor unions, code officials, utilities, building departments, architects, and builders. Through trial installations and simulation studies of actual conditions of commercial implementation, many potential problems could be identified and overcome in advance.

4. Commercial Readiness

The commercial readiness phase is made up of two stages — development and demonstration. During the development stage, the technical feasibility of the invention is proved. Also, the technology is refined into a form suitable for application. There is a big difference between the basic invention or concept stage and the instrumentation of the invention into a form suitable for the commercial readiness stage. Many new energy technologies have not yet finished the concept stage of development. Nonetheless they receive a lot of attention as possible solutions to the energy dilemma (even in the short term) because their basic concept seems to imply a virtually inexhaustible supply of new/nonfossil fuel based energy. Many people do not seem to understand that a lot of development (and time) must often be called Research, Development and Demonstration (RD&D) or just Research and Development (R&D). At this point federal funding and assistance is removed and the invention must be finally tested in the marketplace. However, testing requires time and there may be long lag times before the invention is widely accepted. For most products this is acceptable since quick application is not in the public interest and the time lag may produce a better product through operation of the marketplace and refinement of the product. However, with the short and intermediate term aspects of the energy dilemma, most of the benefits of government intervention are obtained only if the invention achieves rapid application. In this case there are public benefits to a continued government role to encourage implementation of the demonstrated invention.

Although the need for government action to speed implementation is often ignored, sometimes the need is recognized. The Federal Energy Administration (FEA) is currently taking an active role in encouraging the implementation of solar energy devices which have completed ( or nearly completed) demonstration. Frank Zarb, Administrator of the FEA, emphasized the need for implementation efforts in testimony to the House Subcommittee on Energy Research, Development and Demonstration of the Committee on Science and Technology. FEA's implementation program is predicated on "a realization that without an aggressive federal program to commercialize solar energy technologies, the significant fossil fuel savings projected as a result of solar energy in The Project Independence Blueprint Report will not be realized" (Reference 1-11, p. 8).

5. Diffusion of Innovation

The last phase in commercial development is the diffusion of innovation. During this stage the technology is commercially manufactured, distributed, used, and many of the real obstacles to widespread use are encountered. It is diffusion of innovation which results in various social, economic, technical, political and environmental consequences.

The diffusion of innovation phase may be divided into three overlapping stages:

(1) Commercial "beachhead" implementation — the launching of a commercial venture by industry, possibly with assistance from the government, which is sufficiently large and realistic enough to test the marketplace in selected regional areas, to obtain data on the full costs of such production, distribution, installation and maintenance, and to determine whether the diffusion of readiness activities have adequately paved the way for overcoming market constraints that might exist;

(2) "Take-off" of commercial diffusion — increasing the investment in production and distribution facilities which is matched to the new products rate of market penetration; growth of competition; falling away of government financial support or other facilitative mechanisms; and convincing indications of the product's market acceptance;

(3) Sustained commercial activity — the new product is now firmly established in the marketplace in competition with other products and subject to normal market forces.

During the diffusion of innovation, the innovation process itself (in terms of product improvement through feedback from field experience) and diffusion of readiness (through continuing and escalating interaction with the entire industry and public which is receiving the innovation) will also occur. In this sense, the various phases may begin at sequentially later times, but each will continue to interact and modify each other. Table 1-1 summarizes the activities which occur in each of these stages.

Table 1-1. Stages in Commercial Development: The Growth of a Technology or Process From Scientific Invention Through Research and Development to Diffusion of Innovation

| | | |
|---|---|---|
| A. | Innovation: Basic Science Research & Technology Stages: | |
| | Stage 1 - Invention | - New idea or concept, no significant research begun. |
| | Stage 2 - Research | - Understanding the underlying principles and development of a sound theory or experience for technology development. |
| B. | Commercial "Readiness" Stages: | |
| | Stage 3 - Development | - Technical feasibility proven. Refinement of technology continues. |
| | a - conceptual<br>b - prototype<br>c - technical and economic studies | |
| | Stage 4 - Demonstration | - Technical application at a scale similar to commercial application. Primary economic questions are raised and answered. |
| C. | Diffusion of Innovation Stages: | |
| | Stage 5 - "Beachhead" Implementation | - Market acceptance and profitability tested. Final "debugging" of commercial operational problems. |
| | Stage 6 - "Take-off" or Commercial Diffusion | - Increasing use of the new product and growth of sales/distribution and servicing networks. |
| | Stage 7 - Sustained Commercial Activity | - New product is firmly established in the marketplace. Penetration is greater than 1%. |

Frequently technological innovations are gradually diffused into an industry doing business as usual. Today, however, the energy situation puts the U.S. in the position of fostering crisis-propelled innovations. There are numerous pressures for more and cleaner forms of energy, while at the same time there are a variety of new technologies and techniques for energy use which offer the promise of some relief from these pressures. Research has shown that the recognition of a serious need, which in turn creates a potential market, is often a far more important stimulus to a new product development than industry or university based R&D projects (Reference 1-12).

Yet there is a danger in believing that the emergence of a crisis — and widespread recognition of the need for programs to address the crisis — will automatically lead to effective responses. While legislation must be introduced and passed in response to the political imperative for action in the face of a national problem, it may be drafted without a strategic examination of the issues involved, and therefore may be counter-productive or simply ineffective. For example, legislation which requires the design and operation of buildings to meet energy performance specifications — without providing mechanisms for successful implementation — could result in criteria not being met.

In addition, a crisis-environment can create a frantic search for instant panaceas by policy makers, researchers, the media, and general public. In such an environment, there is often failure to recognize and make known the problems and barriers that go along with the potential promised by new technologies. When, because of these barriers, the technologies fail to live up to some of their promises, the general public, whose continued support may be critical to effective development and commercialization, can become frustrated and disillusioned. However, without a sense of crisis and urgency, it is unlikely that any major efforts — such as legislation to promote resource conservation and management — would be rapidly introduced and implemented.

# SECTION II

## OVERVIEW OF SOLAR ENERGY TECHNOLOGIES

It is the business of the future to be
dangerous; and it is among the merits
of science that it equips the future for
its duties.

Alfred North Whitehead

Busy old fool, unruly sun
Why dost thou thus,
Through windows, and through curtains,
Call on us ?

John Donne
<u>The Sun Rising</u>

The use of solar energy has been proclaimed at various times over the past 100 years as an ideal energy source. Renewed interest in solar energy has been sparked by energy and environmental problems. Basically, a solar energy system converts sunlight into heat, electricity or other forms of energy, which can then be used to supply various needs. The simplest of such systems are small solar water heaters, once widely used in southern Florida in the late '30s and early '40s. More complex systems — such as the conversion of collected solar heat into mechanical and electrical energy — have been demonstrated in prototype and laboratory applications; other concepts, although technically possible today, have yet or are about to be designed and tested.

In many parts of the country solar technologies, if made commercially available, could supply over 70% of the electrical and thermal requirements for residential buildings as well as for many types of commercial, institutional, and industrial structures. Supplementary fuels and/or electricity would be required only during periods of cloudy weather exceeding several days.

Solar systems promise a number of substantial benefits. Solar energy is a renewable energy resource rather than a depletable resource. It is widely available and is not subject to foreign control (except, perhaps, in a theological sense). Direct conversion of sunlight into heat and electricity has no repercussions in terms of land destruction, air pollution, or other types of environmental degradation often associated with more traditional forms of energy.

Although such systems will almost invariably raise the first cost of a heating/cooling system, the use of solar energy to provide space heating, water heating and cooling is competitive on a lifecycle cost basis with all electric systems (at 1973 electricity price levels of $0.05/kWh); no such competitive advantage will be possible with natural gas until gas prices rise dramatically (which is not expected to occur before 1985).

## A. INTRODUCTION TO SOLAR ENERGY

In order to understand the possibilities for solar energy in the context of the energy crisis, one must know something about the technology.

Solar energy as defined by many experts covers a wide range of energy possibilities. Often included is wind energy, bioconversion of crops into either hydrogen or direct burning vs fuel, and tidal energy which is produced by the relative motion of the earth/moon and sun system. In fact, the sun is a basic force in our lives; one that runs so deep it is almost impossible to draw a boundary around solar energy. Petroleum and coal were produced from living matter which relied on the sun and which decomposed under pressure into oil, coal, etc. The falling water which drives hydroelectric plants also could be classified as solar since the evaporative process raises water from the oceans and other bodies of water and effectively transfers it to the mountains as snow or rain which eventually can produce hydroelectric power.

Although solar energy can be defined to embrace a wide variety of energy options, I shall narrow the definition to include only two direct solar energy processes. The first is solar thermal processes; that is, processes that rely on the sun to produce heat which is then used to produce usable energy. Included in this type of solar energy are both the low temperature (below 200°F) solar energy forms which can be used to heat and cool buildings, and high temperature solar energy forms which can be used to produce electricity.

There are five basic forms of solar energy: solar thermal, photovoltaic, bioconversion, ocean thermal, and wind. Each of these relies on a different underlying basic technology and is in different stages in the application diffusion process. Although the details of each of the technologies used to capture a particular form of solar energy can be quite complex, at a more general descriptive level each form can be characterized by a basic technology, a type of application and feasibility status in terms of commercial development.

In order to provide a context for understanding the implementation and policy questions regarding solar energy, a general description of each technology will be given in this section. Because the basic thrust of policy issues and implementation are in part to encourage the use of those solar technologies closest to commercial diffusion, the general description of solar technologies will be followed by a discussion of several actual applications which have been tried.



### 1. Solar Thermal

Solar thermal energy uses direct energy from the sun to heat a fluid in order to provide useful energy for some purpose. Low temperature applications can be used to heat and cool buildings, provide water heating and for agricultural food drying. The basic unique technology of this form of solar energy is the flat plate collector.

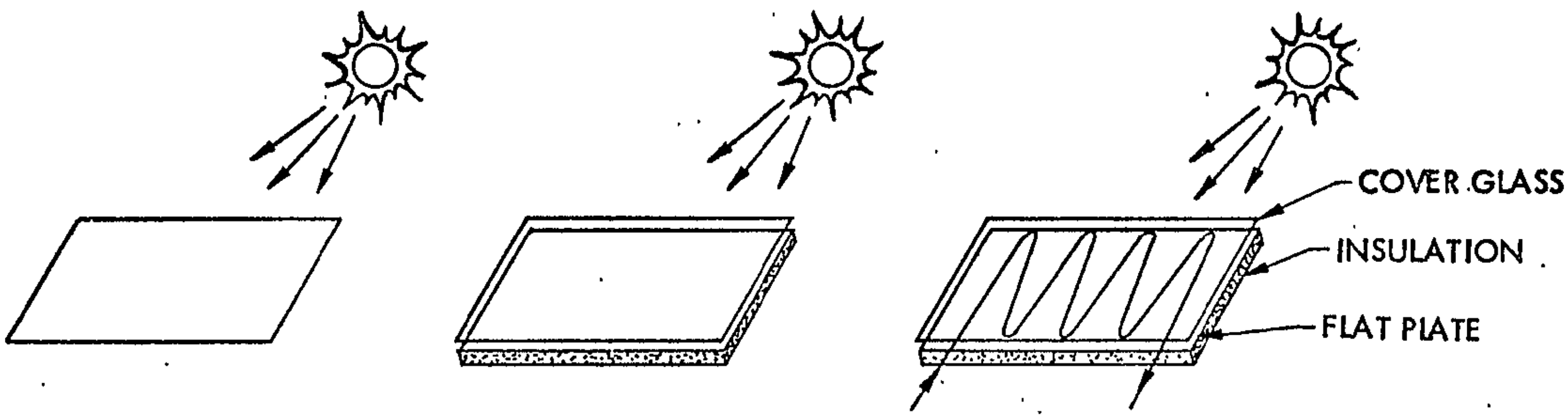
Flat plate collectors, generally constructed of metal, glass and insulation, make use of both the direct sunlight and diffuse light scattered by clouds and atmospheric haze. A flat metal plate, painted black or otherwise treated to absorb most of the sunlight falling on it, heats up. At the same time, the absorbed plate cools by reradiation of infrared energy, by convective cooling from the surrounding air, and by conduction cooling to anything supporting the plate. The conduction losses and air convective cooling can be minimized by insulating the back of the plate. Heat is prevented from radiating away by placing sheet glass or another clear material over the top of the plate, with a half-inch of space between the absorber metal plate and each of the clear covers. If glass is used (a greenhouse effect), light passes through the transparent covers to heat up the metal plate, but reradiation of the infrared heat is blocked by the cover glasses, trapping it in the space between the plate and the glass. The metal plate, thus, becomes much hotter than it would without the cover glasses and insulation. On a clear day, even in cold weather, a flat plate solar collector can reach temperatures of over 300°F when oriented to face the sun.

By running a fluid over the black plate, or through coils or tubing attached to the plate (Figure 2-1), this heat can be drawn away and used for water heating and space heating; it can also be used to operate a heat-actuated air conditioning unit. To date the simplest, and only commercial, application of this principle is found in solar water heating.

The temperature of the collector drops as heat is withdrawn by the fluid running through it. Since even the best constructed collector will lose some of its energy to the surrounding environment through convection and reradiation, the lower its operating temperatures, the more efficiently it converts sunlight into heat in relative terms. In most applications, flat plate collectors operate between 100 to 180°F, at efficiencies ranging between 30 and 60%.

In addition to the flat plate collector, low temperature solar thermal applications generally require five other elements for normal operation, as shown in Figure 2-2. These are a fluid (1) which picks up the solar energy from the collector, and a distribution system (2) such as pipes or ducts which move the fluid to the place where the energy is to be used. Some of the energy may be put into a storage device (3) (such as a large tank). A control system (4) is often used to automatically transfer the stored solar energy to the place where it is needed. The energy is removed from the fluid (5) for the particular required application.

Low temperature solar thermal systems have been built for a number of years. In several countries water heaters have achieved significant commercial use. In fact, 50,000 solar water heaters installed over 20 years ago in Florida were used until the advent of cheaper electricity (Reference 2-1). For space heating and water heating, the cost of these systems is less than electricity but more expensive than natural gas and they are in stage five of




FLAT BLACK PLATE ABSORBS SOLAR ENERGY, HEATS UP

TOP COVER GLASS PREVENTS HEAT FROM RADIATING AWAY (THE GREENHOUSE EFFECT) INSULATION PREVENTS HEAT FROM ESCAPING BACK OF PLATE

FLUID (THERMAL TRANSFER) CARRIES HEAT TO THERMAL STORAGE UNIT FOR WATER HEATING, SPACE HEATING, AIR CONDITIONING, ETC.

**Source: New Energy Technologies for Buildings, 1975**

Figure 2-1. Elements of the Flat Plate Solar Collector

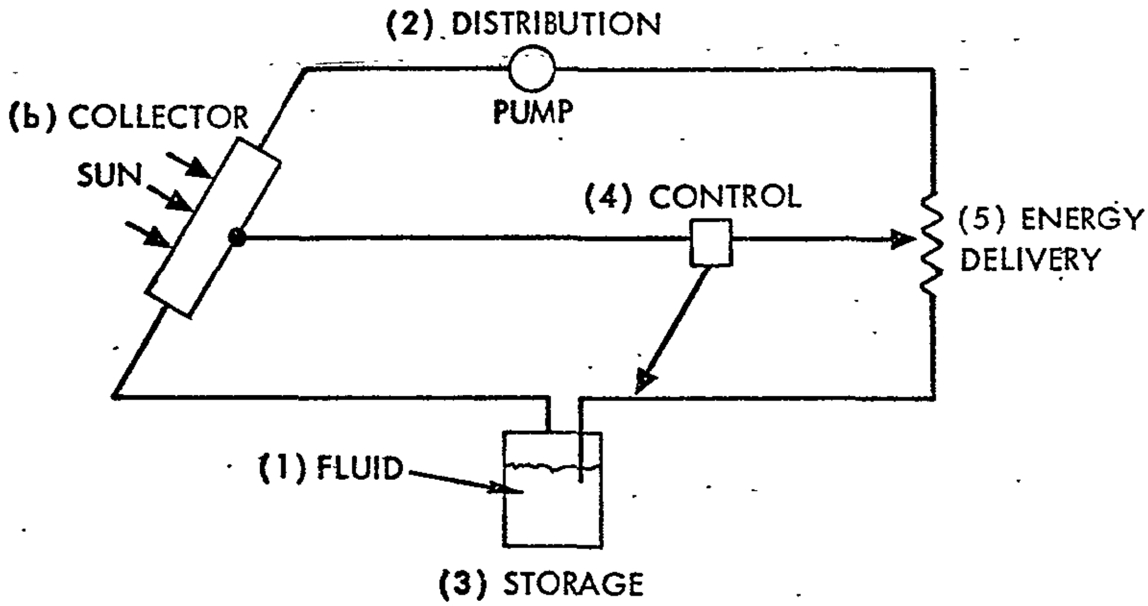



Figure 2-2. Elements of a Solar Thermal Energy System for Heating a Building

the commercial development process. Solar space cooling has not achieved this advanced state and is still in the transition from development (stage three) to demonstration (stage four).

The second type of solar thermal energy technology is high temperature solar thermal applications. This form of solar energy can be used to produce electricity in central power plants by heating a boiler to the 1000 °C range and using this high temperature to run a turbine and produce electricity. The basic technology of high temperature applications requires the use of focusing collectors.

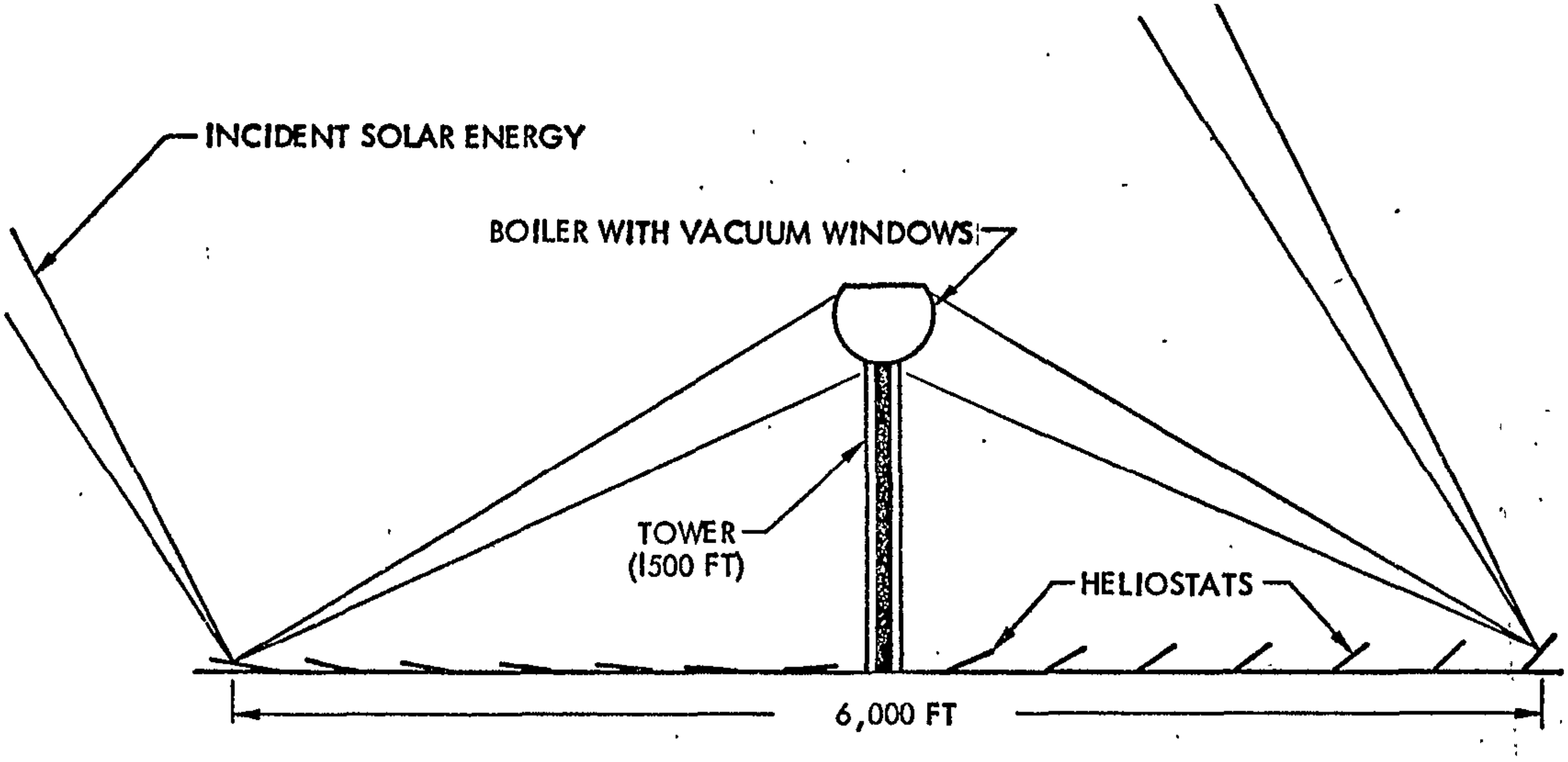
In one form of focusing collector, a fresnel lens or a parabolic cylindrical mirror focuses sunlight on a heat absorbing pipe enclosed in a transparent jacket. By removing the air from the space between the jacket and the pipe, heat conduction from the pipe to the jacket is eliminated. A high boiling temperature fluid or a gas is passed through the pipe and picks up the heat generated by the focused sunlight. In this type of collector, the heat transfer fluid can easily reach temperatures of 300 to 600°F, and can be used to operate an engine for units as large as compression refrigerators and electric generators of the type used in central electric generating plants.

Focusing collectors were used to operate engines as long ago as 1873. John Erricson, the designer of the iron-clad Civil War vessel, the Monitor, coupled such a collector to a hot air engine of his own design. Many later experiments were conducted with this type of collector to show feasibility of using solar-generated heat to operate engines ranging from water pumps in Pasadena, California (1909) and in the Egyptian desert (1912), to a small electric generator developed by Dr. Horace Abbott of the Smithsonian Institution (1937) (Figure 2-3). There are virtually no contemporary applications of focusing collectors, with the exception of the experimental solar furnace in operation at Odeillo in the Pyrenees mountains of southwest France.

The advantages of focusing collectors over flat plate collectors include the ability to reach higher temperatures and to operate engines more efficiently than is possible with flat plate collectors. Disadvantages include the need to maintain the collector oriented toward the sun (through some type of tracking mechanism) and the need for carefully made lenses or parabolic surfaces. For these reasons, focusing collectors are generally more expensive than flat plate units at this time.

Two types of central power plants are proposed using this high temperature technology. The first has actually been used in a 50-kW plant in Italy where a set of steerable mirrors focus solar energy on a boiler as shown in Figure 2-3 (Reference 2-2, p. 49).

The 150-ft diameter, 1500-ft high tower could cost about $15 million and the boiler would operate at 1000°C. A. F. Hildebrandt (Reference 2-3) estimates that the total cost of heat collected by this plant would be about $0.50 per MBtu (natural gas currently costs $1.50 for residential customers)




Source: Williams

Figure 2-3. Tower Concept for Power Generation

A second type of high temperature solar thermal generator station has been proposed by Meinel and Meinel at the University of Arizona (Reference 2-4). A solar form covering 13,000 $mi^2$ of desert in the southwest United States, using circulating liquid metal such as sodium or NaK to extract heat from a large set of focusing solar collectors has been proposed. The energy would be stored in a phase-change salt at temperatures about 1000°F. Electricity would be produced from a high pressure steam turbine at an estimated cost of $0.50 per MBtu for the solar energy collected (References 2-5 and 2-6). A schematic of this type of system is shown in Figures 2-4 and 2-5.

Such high temperature solar thermal systems are still in the research and development stage (stages 2 and 3) although prototype systems have been built in Italy and a bench model of the solar form has been built by the Meinels.

The third type of solar thermal systems are so-called solar furnaces which operate at very high temperatures (above 3400°C). These systems utilize large parabolic concentrators and are principally used for research and industrial applications such as melting tungsten. The largest solar furnace producing one megawatt was built at Odeillo-Font Romen in the French Pyrenees in the 1950s. Similar but smaller furnaces have been built in the Soviet Union, Japan and the United States. Figure 2-6 is a schematic of a solar furnace.

## 2. Solar Photovoltaic

Photovoltaic is the second principal form of solar energy conversion; it is a process that converts solar energy into electricity and is the operating principle of solar cells used to provide power for most U.S. launched spacecraft (Figure 2-7).

A solar cell is a specially treated wafer of silicon, typically 2 cm square and about 0.02 cm thick. The bottom surface of the cell is coated with a metal; the top surface has a metallic grid covering about 10% of the exposed silicon. When light strikes the cell, a voltage appears between the top and bottom electrodes, and current flows between them (Figure 2-8).

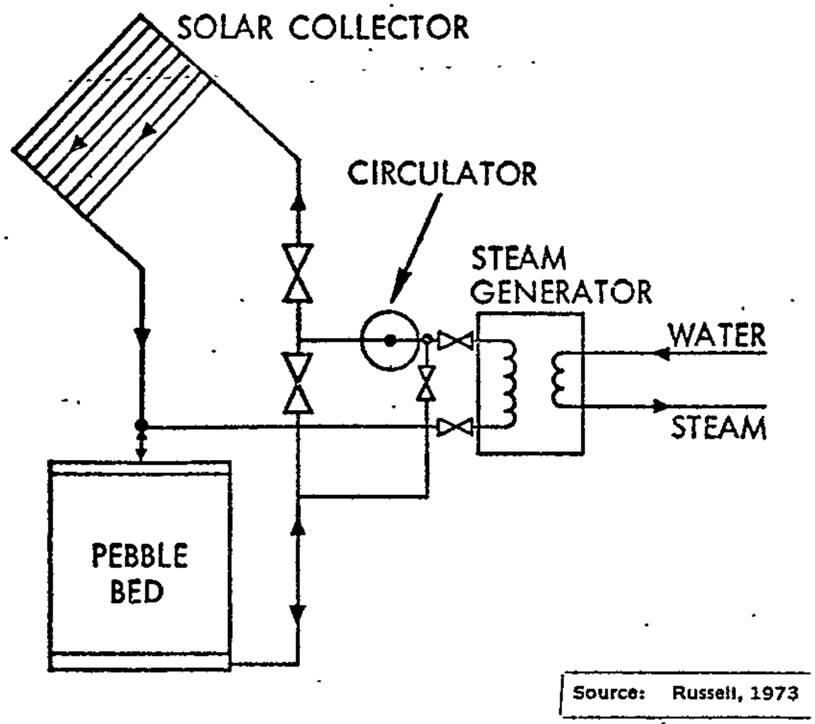



Figure 2-4. Flow Diagram for a Solar Thermal Power Plant

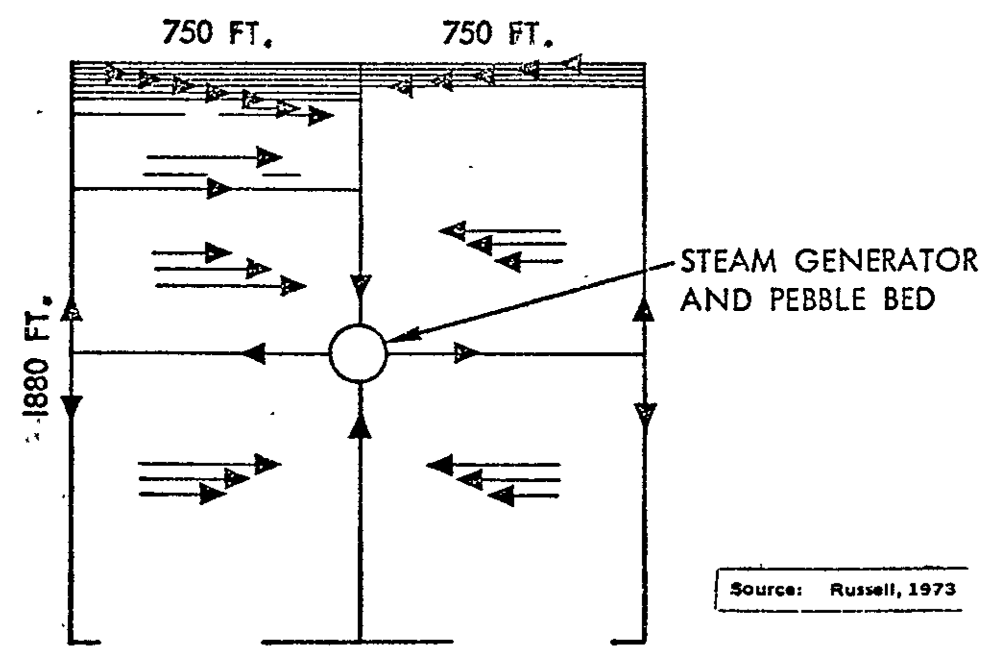
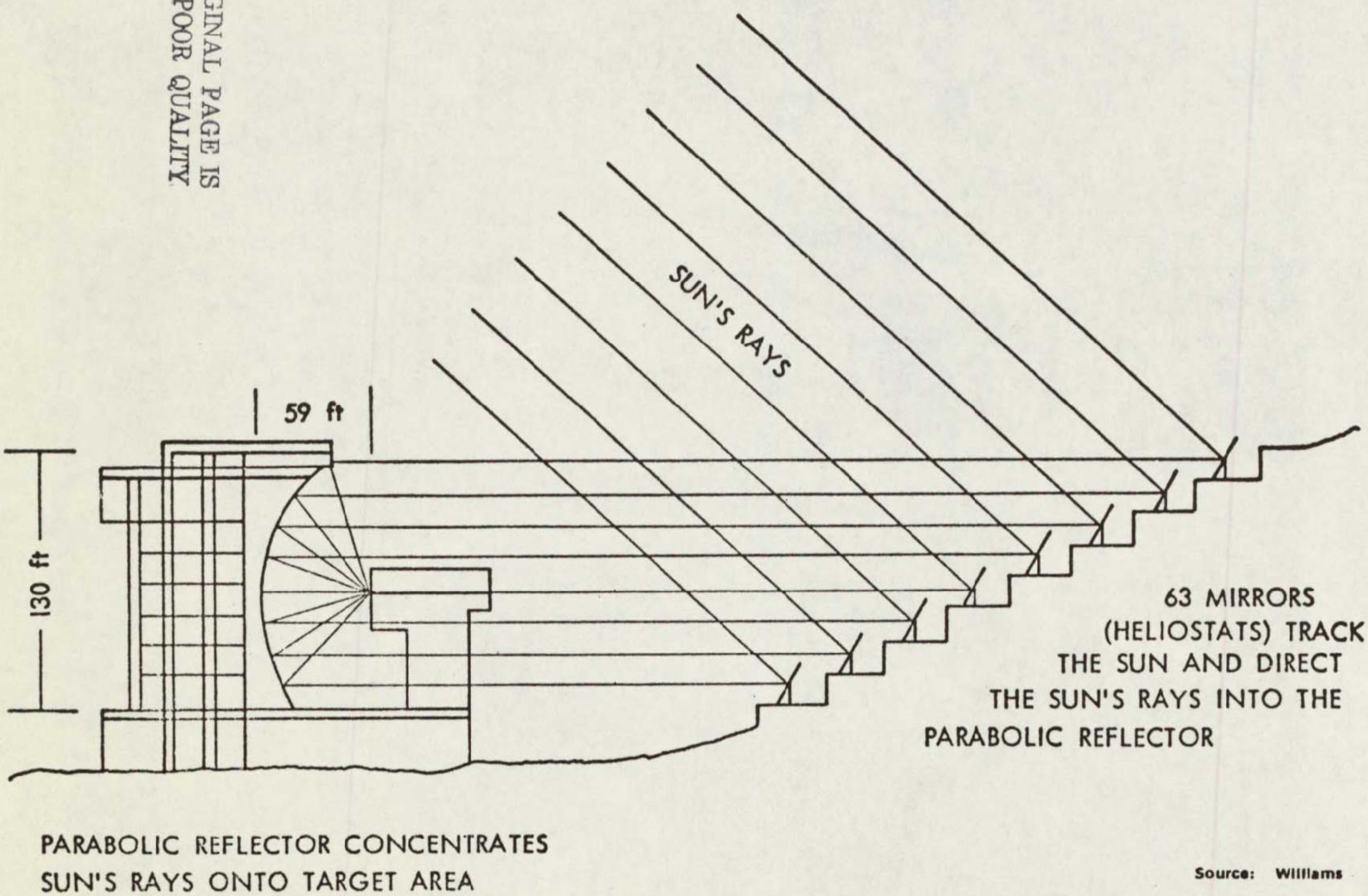



Figure 2-5. Module of a Fixed Mirror Electric Power Plant




Source: Williams

Figure 2-6. Large Scale Solar Furnace

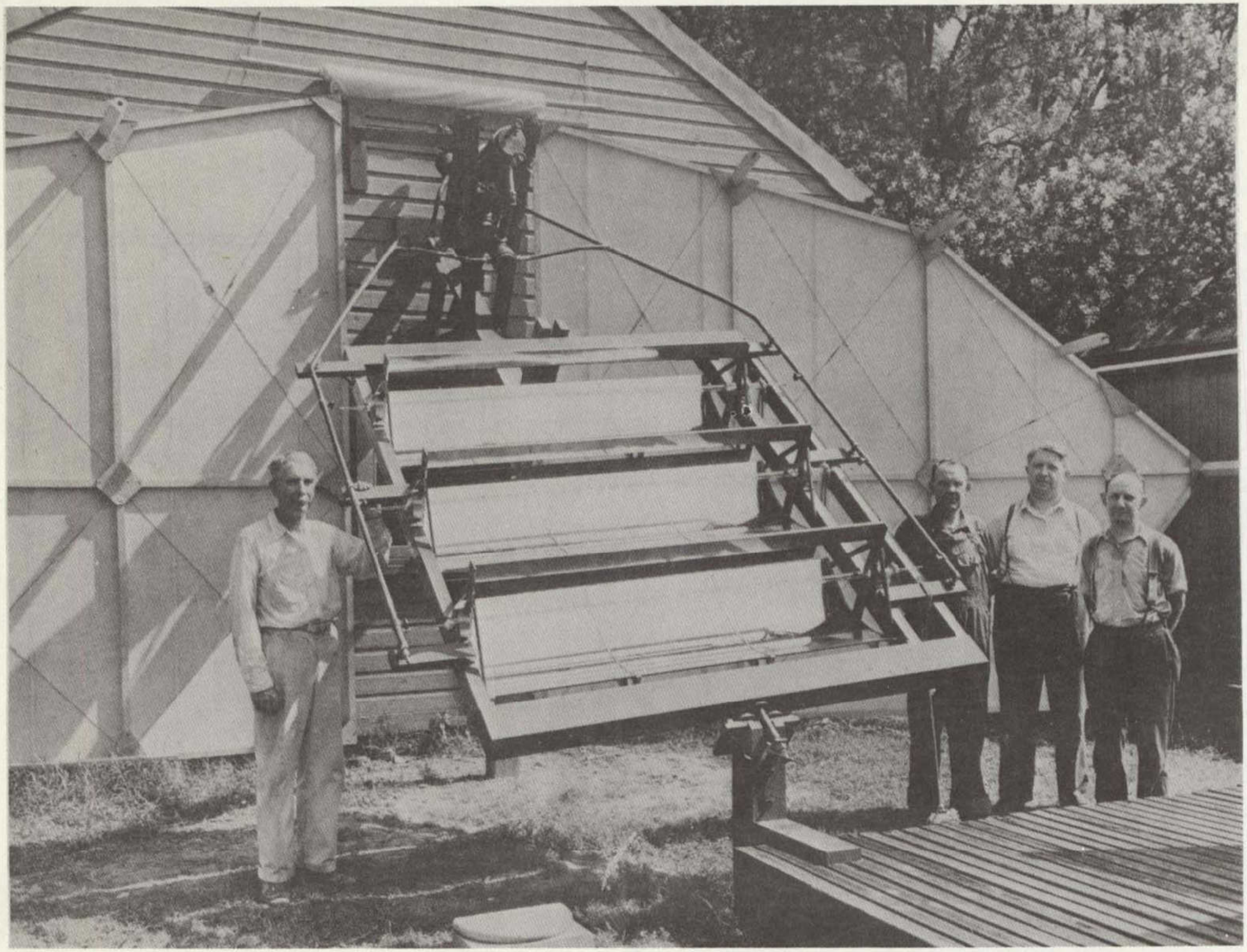
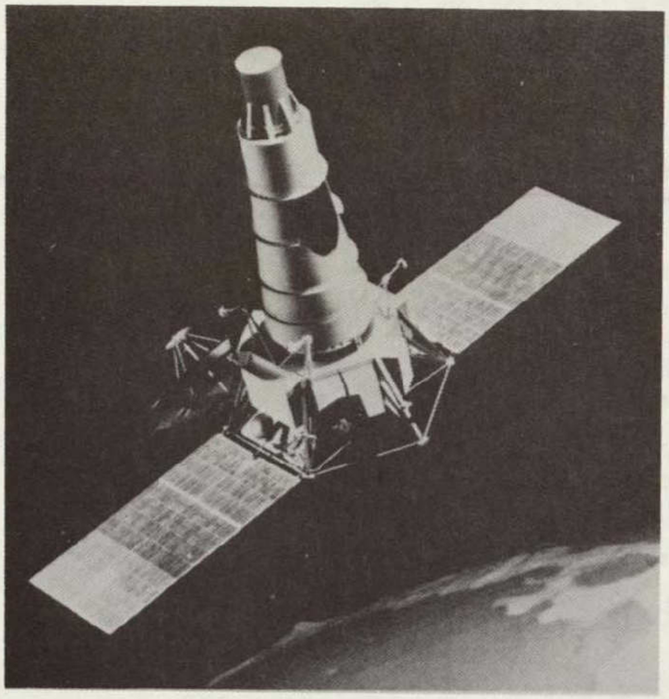


Figure 2-7. Focusing Solar Collectors Driving an Engine/Generator



Solar panels on a model of a RANGER spacecraft indicate how thousands of individual cells are mounted together in a structural and electrical matrix. In Skylab, these panels supplied tens of kilowatts.

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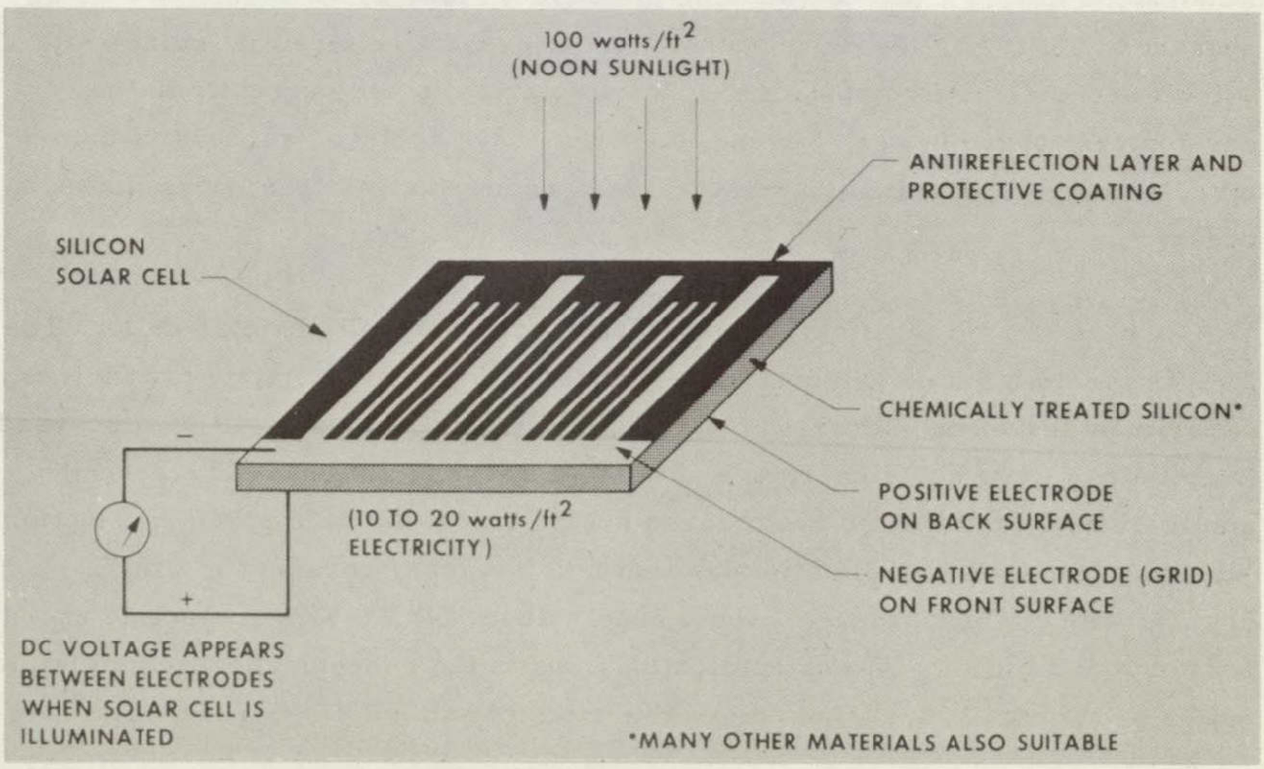
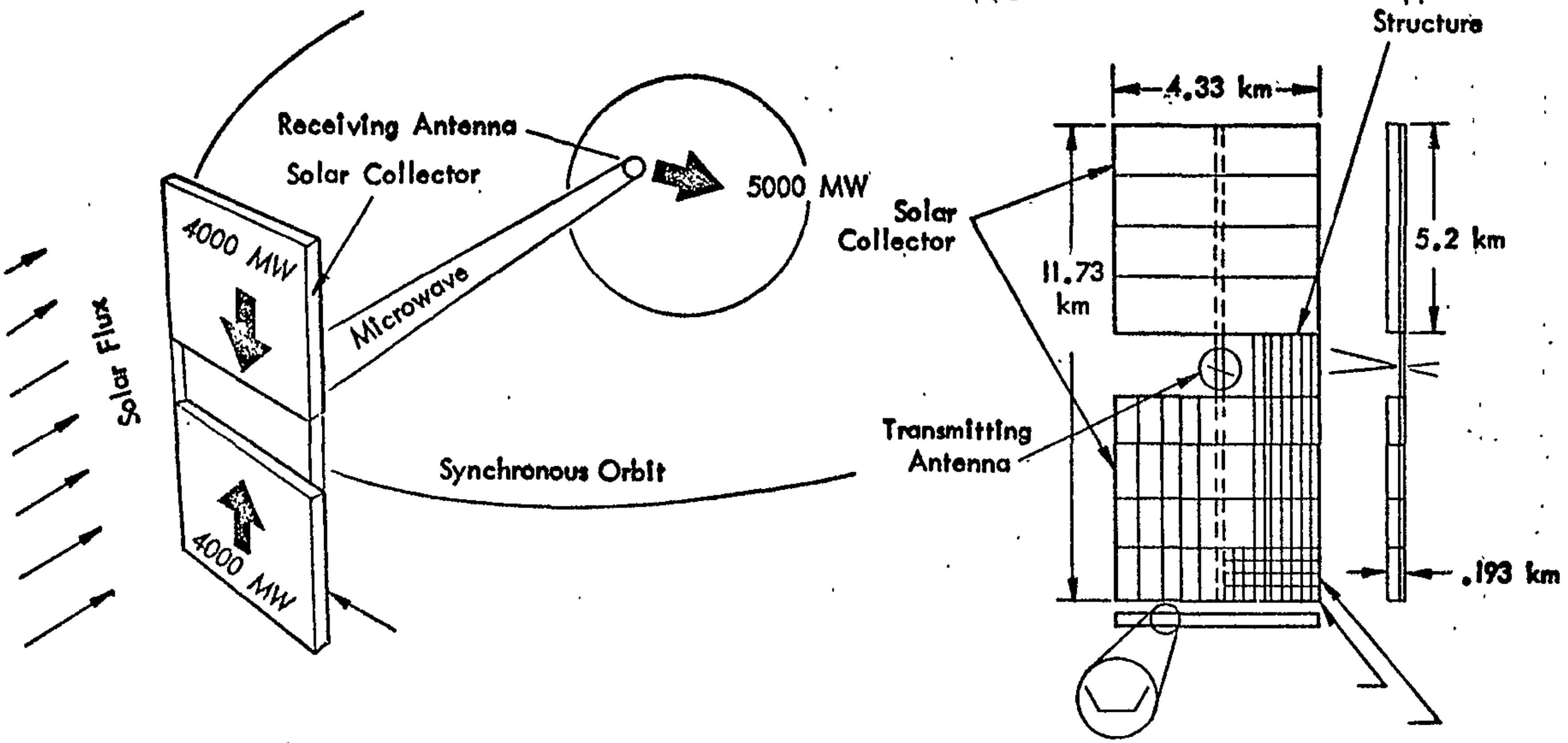



Figure 2-8. Direct Conversion of Sunlight Into Electricity

Conversion efficiencies range from a few percent in cadmium sulfide cells to over 18% in experimental silicon cells. To provide the large amounts of power required for a spacecraft, these cells are connected together and placed in large arrays, which then serve as the power sources for the spacecraft. Although these arrays are quite expensive – $100,000 to $500,000 per peak kilowatt in space – their high costs are justified in space craft applications where no other source of energy can be supplied as reliably and easily. For applications on earth, such arrays will have to produce electricity at rates comparable with other options. Since the photovoltaic collector converts sunlight into electrical energy at less than 15% efficiency but absorbs over 90% of the sunlight falling on it, the remaining energy is converted into heat which must be removed to prevent it from further decreasing the operating efficiency of the solar cells. This heat can be used for water heating or other purposes, in effect causing it to behave like a flat-plate thermal collector as well as an electric power generator.

Currently there is a $750 million 10-year project at the Jet Propulsion Laboratory to find a way of reducing the cost of solar cells from $1-20/W at present to $0.20/W, the price at which most experts believe that solar cells will be economically competitive. Thus, solar cells are currently in the development phase (stage 3) even though they have achieved successful commercial use in space and for remote power needs such as free buoys in the ocean.

There are three principal applications for photovoltaic solar cells. The first is for distributed photovoltaic systems to provide electricity for individual experimental houses, several of which already exist. These will be discussed later, along with low temperature solar thermal applications. The second application of photovoltaic is for large scale central electric power production. Williams (Reference 2-2) estimates that a solar array covering 192 $mi^2$, coupled with pumped storage, would supply about 14,300 MW of electric energy for about $60 billion. These applications are in the conceptual stage and would not be economically justified unless the price of solar cells is reduced to $0.20/W.




Source: Glaser, et. al., 1971

Figure 2-9. Geosynchronous Solar Power Plant the sun. Wind energy has been around for a long time. The principal problem with its use seems to be the combined difficulty of storage and predicting power supply fluctuations.

The potential from wind energy is very large. A committee sponsored by the National Science Foundation found that by the year 2000, a major wind energy development program could result in an annual yield of 1.5 trillion kWh of electricity. This is roughly the equivalent of the U.S. 1970 electrical energy consumption.

In 1939 a 1 1/4-mW wind power plant was built on Grandpa's Knob near Rutland, Vermont. It delivered power to the utility grid during 1941. Full power was achieved for wind velocities in excess of 30 mph, which occurred 70% of the time. The cost of the power plant was slightly over $1 million (132). However, largely because of World War II, the utility had trouble obtaining reliable parts and the station was finally dismantled in 1945 after one of the blades broke during a storm.

One promising possibility is the combination of wind power with hydroelectric so that the latter could be used when the wind power fell off. The largest generator built recently was an 800-kWe plant built in France in 1958-60. Small wind generators (5 kW) can be purchased for about $2,200, including freight. The application appears to be nearly economically competitive for some cases.

Several wind generators are in use for electric generation and pumping water. A company in Switzerland sells a 6-kWe wind generator with complete automatic controls for about $3,000. In 1970 William Heronemus of the University of Massachusetts proposed a network of over 600 large wind generators which could provide enough electricity to meet most of the needs of the northeastern United States at costs competitive with fossil fuel electric plants. In 1972 three wind generators were built by Robert Reines in New Mexico for his unique home. The largest generator produces 5 kW of electricity. Storage is provided by a bank of 16 heavy-duty batteries which can store up to 22 kWh.

The wind generators have supplied current to a full range of appliances including Hi-Fi and television sets, etc. The only commercial distributor of home-sized electric wind generators is the Solar Wind Company of East Holden, Maine. They sell wind generators in the 12-20 kW capacity area which is sufficient to supply 80% of the nonthermal needs of a normal home (Reference 2-8).

The four forms of solar energy conversion are summarized in Table 2-1 which indicates for each form of solar conversion, the applications that commonly use the form, the basic technology which is required to provide the conversion and the status of each form's economic and technical feasibility. Also shown is the stage of commercial development at which each conversion exists. Only the forms of solar energy which are at stage 4 or 5 in the process will be likely to be able to provide energy in the next 10-15 yr on a scale sufficient to be of use to reducing the impact of the energy dilemma. The only two which satisfy this criteria are low temperature solar thermal conversion and small scale wind generators. Low temperature solar thermal could provide a significant fraction (up to 10%)[2] of the energy required to heat and cool buildings and provide water heating. Since about 25% of the total U.S. energy use goes for these thermal demands, the commercial application of solar thermal systems could provide a significant energy savings. Similarly wind power for small scale applications is in the commercialization stage. Also, wind generators and low temperature solar thermal conversion devices complement each other in several ways. Wind generators can provide electricity while solar thermal devices can provide heating and cooling. Further, winds tend to be high on cloudy days when direct solar radiation is low. Combined systems would be a potentially economical way of reducing our conventional energy demands in buildings. Because these devices are nearly economically feasible on a commercial scale, the remainder of this section will discuss the general availability of solar energy and several applications of both of these forms of solar energy conversion.

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[2] There is no technological barrier to sizing the energy system for 100% of the energy requirement. However, the economic optimum size is about 2/3 of the energy use (References 2-9 and 2-10) since beyond that size diminishing margin returns occur.

Table 2-1. Summary of Basic Forms of Solar Energy Conversion and Applications

| Solar Energy Type | Application | Basic Technology | Feasibility and Status |
|---|---|---|---|
| 1. SOLAR THERMAL | | | |
| A. Low Temperature | Water Heating | Flat plate collector<br>Well known technology | Economic feasibility if close commercially available in Japan, Israel, Australia. |
| | Space Heating | Flat plate collector<br>Well known technology | Technically demonstrated 90 buildings in the U.S. almost commercially feasible. |
| | Space Cooling | Advanced flat plate Collector design | R&D stage, 3-5 years from real demonstration |
| | Agricultural Food Drying | Well known technology | Can be practical for assist in crop drying. |
| B. High Temperature | Central Power Plant | Technology known but requires refinement | 10 years away from prototype demonstration. |
| | Steam Electric<br>Liquid Metal Electric | Concentrating collectors | Technical problems with large scale application. |
| Very High Temperature | | | |
| Solar Furnace | Industrial High Temperature | Well known technology | Can be used now for some purposes |
| 2. PHOTOVOLTAIC | Electric Power Central Station | Technology known | Cost a factor of 50 to 100 too high. |
| | Geosynchronous | Unknown | Requires launch of large spacecraft. Year 2000 if then. |
| | Distributed | Storage problems | Cost too high (see above) but technically feasible. Can be useful now in remote areas. |
| 3. OCEAN THERMAL | Electric Power | Problems of corrosion | Major technical and economic problems. Prototype 20 years away |
| 4. WIND | Electric Power<br>Small Scale<br>20 Kilowatts | Wind mills<br>Well known for small scale applications | Storage problems and cost but practical for some applications. |
| | Large Scale<br>Over 500 KWe | | |

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Sunlight falling on a building can add a substantial amount of heat to that building. One needs only to recall how warm a room with large windows facing the south and west can become in the late afternoon on a clear day, even during the winter. In large office buildings, vast expanses of glass facing south and west can substantially increase the requirements for air conditioning, in contrast to buildings similarly designed but with the window walls facing east and north. In the past, the unwanted heat gain from solar radiation has been compensated for by mechanical means with air conditioning, shading devices, and more recently, reflecting and heat-absorbing glass. While there have been some attempts to use the incident sunlight to provide a substantial portion of the heating and cooling energy for a building, there have been few efforts (with the exception of one very recent prototype, Solar One) to provide a substantial amount of electricity to a building from solar energy conversion. Only one solar energy conversion device -- the solar water heater -- has experienced significant use, and this has been primarily in those regions where alternative sources of energy for water heating are very expensive.

Use of other forms of solar energy conversion has been limited by technical, economical and institutional considerations. Until recently, the widespread and basically inexpensive availability of a variety of energy sources (coal, oil, natural gas) coupled with the lack of environmental, political or logistical constraints on availability and use of energy have resulted in little interest in the development and deployment of alternative sources of energy or in the introduction and use of energy-conserving architecture, technologies and building management practices.

## 5. Availability of Solar Energy

In the form available at the earth's surface, solar energy presents some obstacles to efficient and economic use: it is subject to daily and seasonable cycles and to variable weather and climatic conditions, and it is of relatively low density, coming in milliwatts per square centimeter, in contrast to megawatts per square centimeter of a high voltage power line. Nevertheless, there is a substantial amount of solar energy potentially available for conversion into other forms of energy for use in buildings as well as for other applications.

Table 2-2 compares the amount of incident sunlight on a horizontal surface on a clear day in various parts of the country and at various times of the year. Typically, from 200 to 700 kWh of solar energy are incident on a 1000-$ft^2$ flat surface (such as a roof) at various times of the year in different parts of the country. By comparison, typical space heating requirements for a well-insulated home can run from 100 to over 200 kWh per day in the northeast during the most difficult parts of the winter, with perhaps a third of that required to heat a similar house in the southwest.

Table 2-2. Availability of Solar Energy on a Clear Day (kWh/hours/1000 $ft^2$-day)

| Location | December | March | June |
|---|---|---|---|
| New York, Chicago | 150 | 390 | 660 |
| Southern California, Arizona | 300 | 480 | 840 |
| Florida | 300 | 480 | 840 |
| Nevada | 210 | 480 | 780 |
| Washington, D. C. | 230 | 425 | 620 |

Figure 2-10, which indicates roughly the amount of sunshine available around the country over the year, illustates that a substantial portion of the requirements of a well-insulated house could be supplied through the use of a rooftop solar collector, assuming reasonable efficiencies (35-50%) for conversion of solar energy into useful thermal energy[3].

Typical residential electricity needs are roughly 20 kWh per day for nonheating and cooling requirements (e.g., household appliance and other



[3] The process of conversion of solar heat into usable energy forms has associated with it different conversion efficiencies. The direct conversion of solar energy into thermal energy, for example, has efficiencies in the 35-50% range; conversion of solar energy into electricity under current practices operates at up to 15% efficiency.

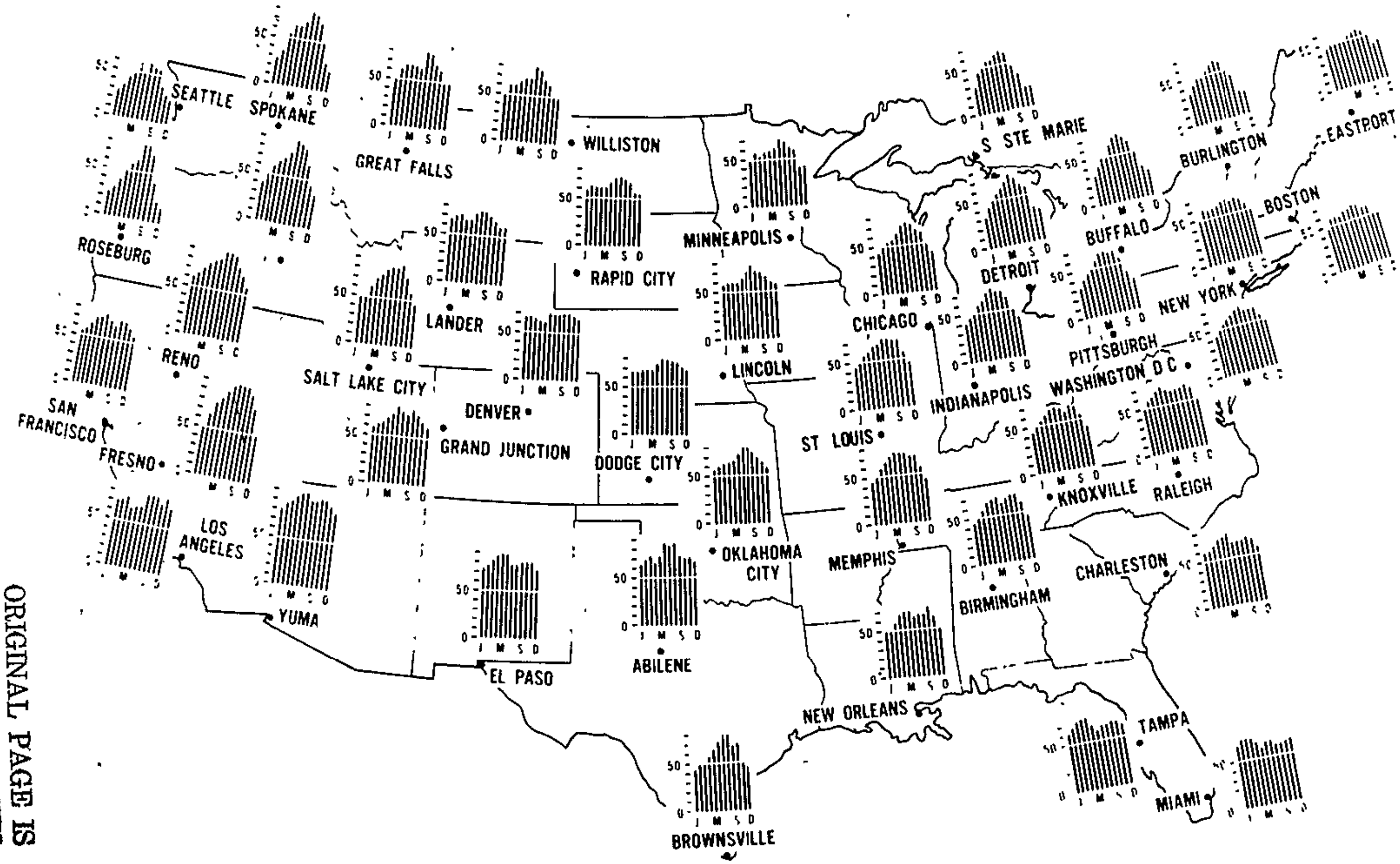




Figure 2-10. Mean Monthly Percentage of Possible Sunshine for Selected Stations (Courtesy of William Cherry, NASA Goddard Space Flight Center, Maryland)

power needs)[4]. Conversion to electricity of 10% of the incident solar energy on a flat 1000-$ft^2$ roof on a clear winter day in Boston could provide two-thirds of this. With appropriate energy conservation measures, virtually all of the nonheating requirements for residential electricity could be provided under these conditions. Availability of a 15% conversion efficiency solar-electric (or photovoltaic) panel, tilted to increase winter solar collection (and thereby decreasing, somewhat, solar collection in summer) would in some 90 kWh being generated on a clear day in the southwest. If, for example, the 3 million residential units in Southern California were equipped with such systems, annual electricity production equivalent to the production of three to five 1,000-MW power plants would be generated from the sun. These figures are not meant to convince people that they should immediately begin implementing the use of solar/electric conversion techniques, but rather to demonstrate the substantial amount of solar energy which is incident on buildings.

The use of solar energy does not require as much shifting of mental gears as might be thought. From the point of view of the mechanical engineer, solar components can be incorporated into electrical/mechanical systems without having to think about such systems in a new way. They are, in fact, compatible with off-the-shelf components such as pumps, heat pumps, heat exchangers and storage elements. Many of these latter components, however, will require newly-developed versions to achieve optimum performance when combined with solar elements.

## 6. Applications of Solar Energy

The simplest as well as only application of solar energy conversion that has been widely used is for domestic water heating. In Japan, for example, several million inexpensive solar water heaters currently are in use: they are essentially plastic water bags with solar transparent tops and black bottoms. They do not store heat well in cool weather, and cannot use

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[4]We differentiate kilowatt hours electric from kilowatt hours thermal in order to distinguish the actual electricity used from the thermal content of the fuel needed to generate the electricity.

supplementary forms of energy; therefore they usually provide heated water only at the end of a generally sunny day. Slightly more complex are the solar water heaters popularly used in Israel and Australia: they combine glass and metal collectors with insulated storage tanks. Electric resistive boosters are often used to guarantee year-round availability of hot water. In southern Florida some 50,000 simple solar water heaters (generally nonsupplemented) were installed from 1945-1960 when the local cost of electricity was very high and alternative fuels were unavailable. When natural gas became regularly available, these systems were no longer of commercial interest, and few are currently produced for the Florida market.

Another commercially available product is a solar swimming pool heating system which utilizes an extruded plastic, low-cost solar collector that can maintain a typical swimming pool at 80°F with south-facing collectors equal in area to about half that of the pool.

Somewhat more sophisticated fuel-assisted solar hot water heating systems are used in hotels and schools in Australia; they operate heating systems as shown in Figure 2-11. Basically, a nontoxic, noncorrosive, and nonfreezing fluid is circulated through the collector. The fluid is heated, then pumped to a heat exchanger mounted adjacent to or within a storage tank. The fluid passing through the exchanger gives up its heat to the cold water in the tank, which has been fed to it by an external source. The cooled fluid returns to the collector for reheat, and the heated drinking-quality water in the tank is stored until needed. At that time, the water is sent to the gas boiler of the house or apartment system where its temperature is further boosted as required for use. This is known as a two-fluid system. It allows the use of corrosion inhibitors and antifreeze in the working fluid without contaminating the house drinking water supply. It essentially functions as a preheat for the portable hot water system in the dwelling unit(s). The extra cost of the heat exchanger and other equipment is in part made up by the ability to use a lower-cost collector. Such systems would require approximately 70 to 100 $ft^2$ of south-facing flat-plate collector for each dwelling unit.

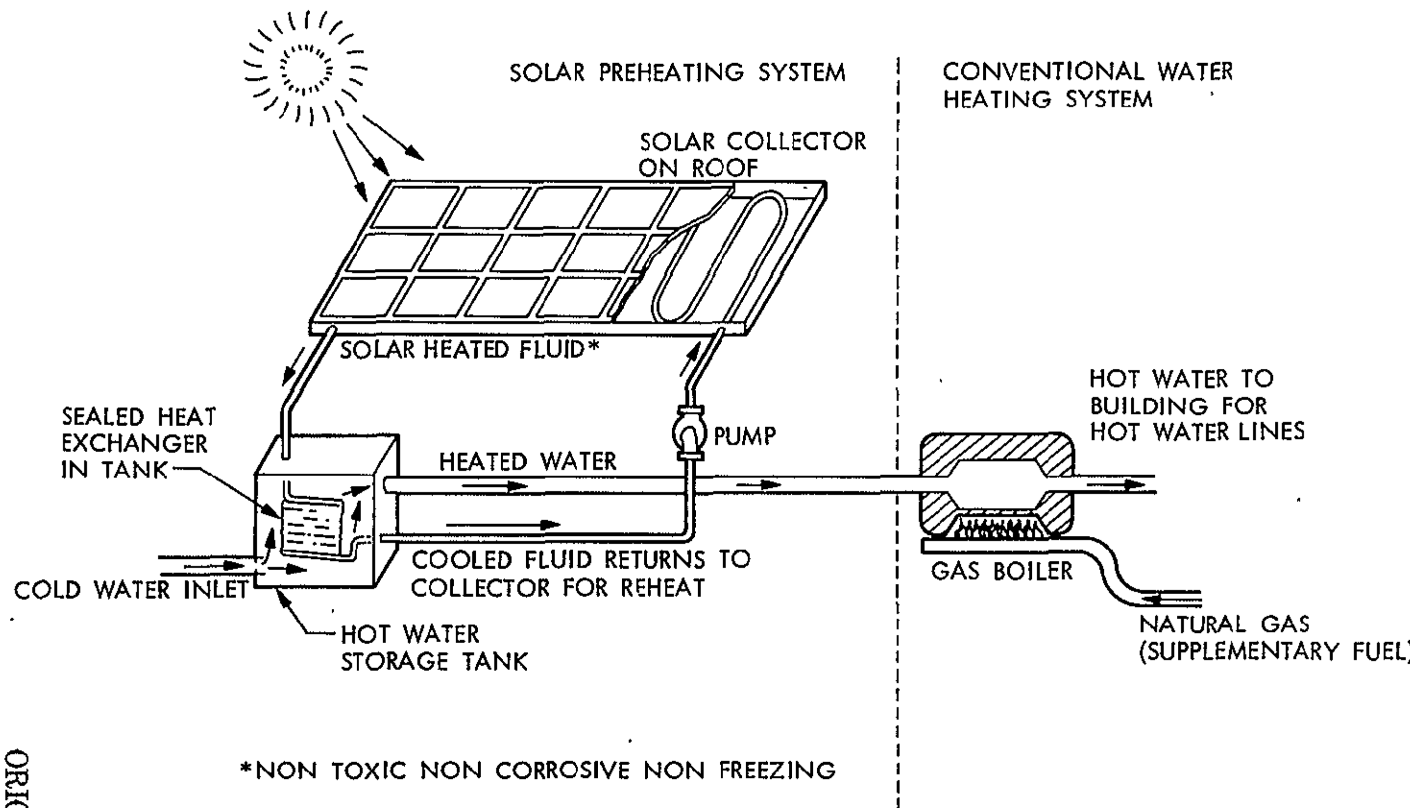


Figure 2-11. Solar Energy and Water Heating

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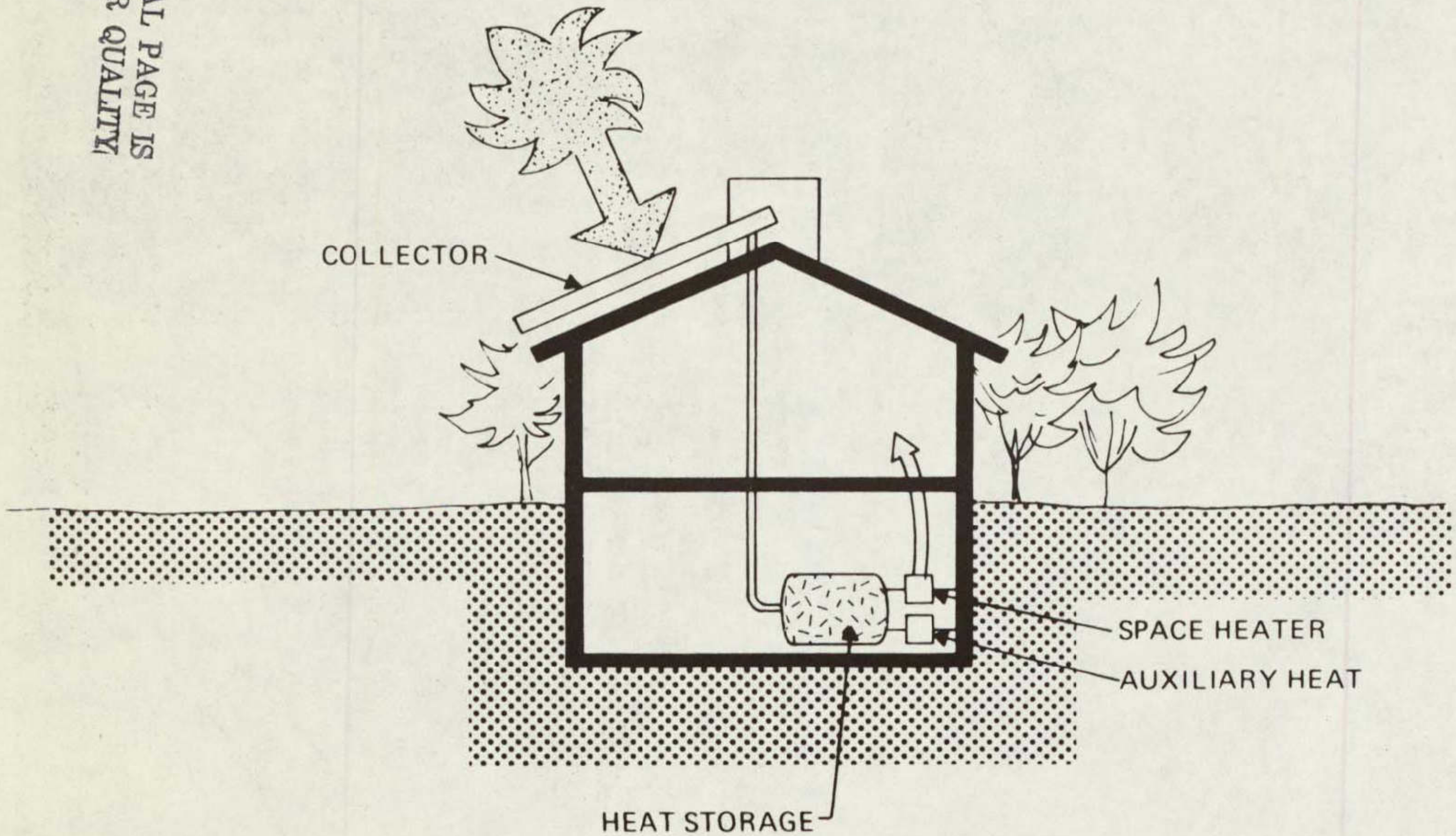
Domestic water heating systems can be extended to space heating through the use of larger collectors and storage tanks in conjunction with conventional hydronic heating systems and baseboard radiators or fan-coil units in the wall or ceiling. Solar collectors with air as the working medium are also feasible. The heated air is then stored in rocks or other materials, and may be combined with conventional forced warm-air space heating systems. Using a variety of approaches, some two dozen buildings in the U.S. have solar heating systems, with several more now under construction or in planning stages. Figure 2-12 illustrates the essential simplicity of such systems.

An experimental solar heated house was constructed by Massachusetts Institute of Technology scientists, engineers, and architects in 1958 after many years of theoretical and experimental work with smaller solar heated buildings (Figure 2-13). This house incorporated a 600-$ft^2$ water heating solar collector with 1500 gal of primary thermal storage. Auxiliary heat was provided by a supplementary oil burner, and hot air was distributed through a fan coil-type of heat exchanger. Direct conversion of solar energy into heat provided roughly half of the winter heating requirements for the two-story, 1450-$ft^2$ house. It should be noted that heating requirements for this heavily insulated house were considerably less than those for more conventional counterparts. The house was designed, built and evaluated as part of an ongoing solar energy research program at MIT, led by Professor Hoyt Hottel.

Also completed in 1958 was a house designed for solar energy researcher Dr. George Löf (Figure 2-14). The Löf home is a flat-roofed one-story structure in Denver, Colorado, with 2000 $ft^2$ of living space. Although originally designed as a conventionally heated home, a solar heating system was incorporated into the final plans. The solar collector consists of two 300-$ft^2$ arrays each containing 20 30-in. by 6-ft panels. Air passing through these panels is heated as high as 175°F. It passes to the basement where some of the heat is used for domestic hot water; then it goes on to either a storage unit or to a gas furnace used for supplementary heat when there is inadequate sunshine. The storage system consists of two fiberboard cylinders normally used as forms for concrete pillars. The insulated cylinders are filled with 11 tons of gravel.




(courtesy Arthur D. Little, Inc.)

Figure 2-12. Schematic of Solar Energy Use in Building

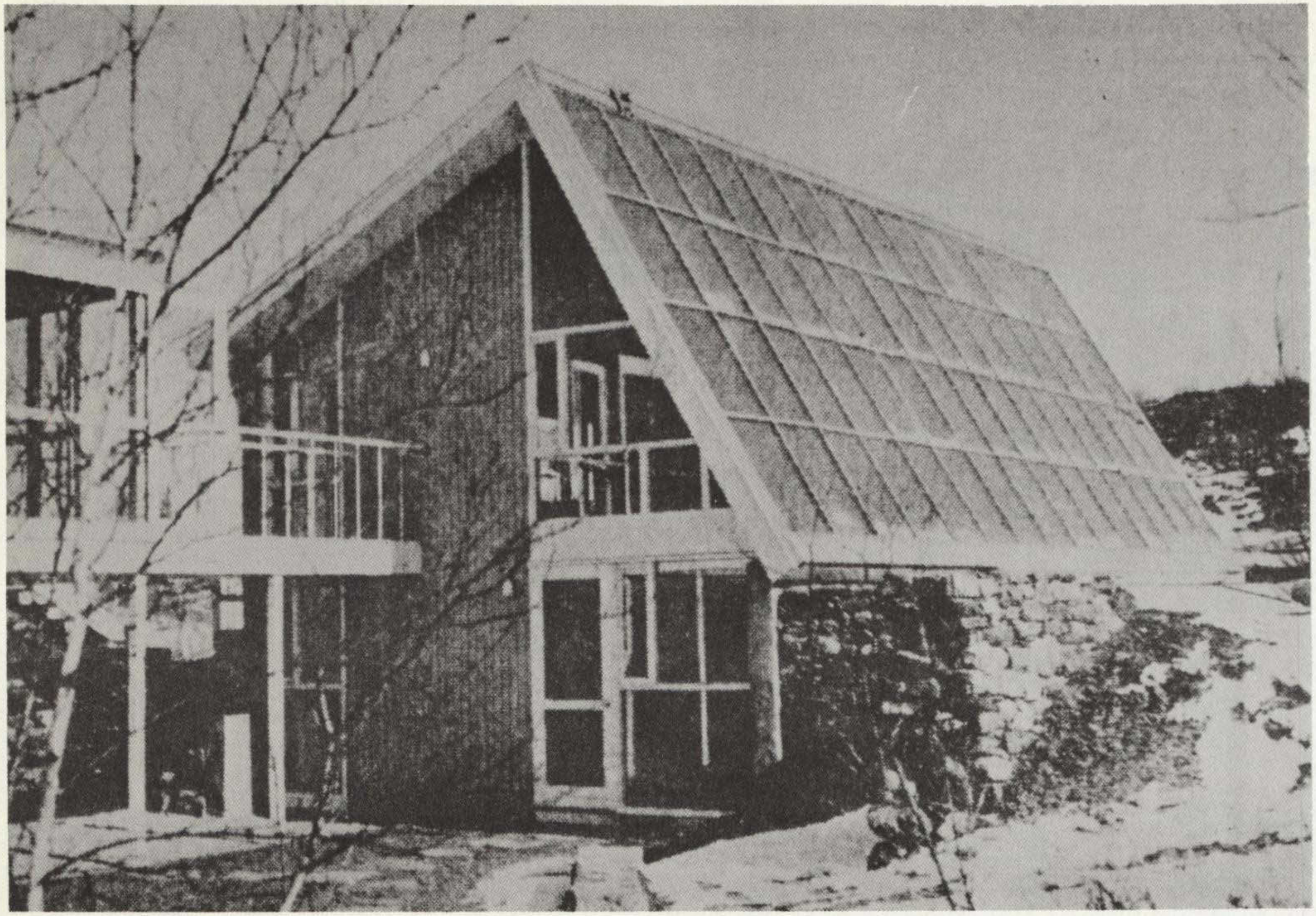


Figure 2-13. The MIT Solar Heated House – Lexington, Massachusetts (1958)

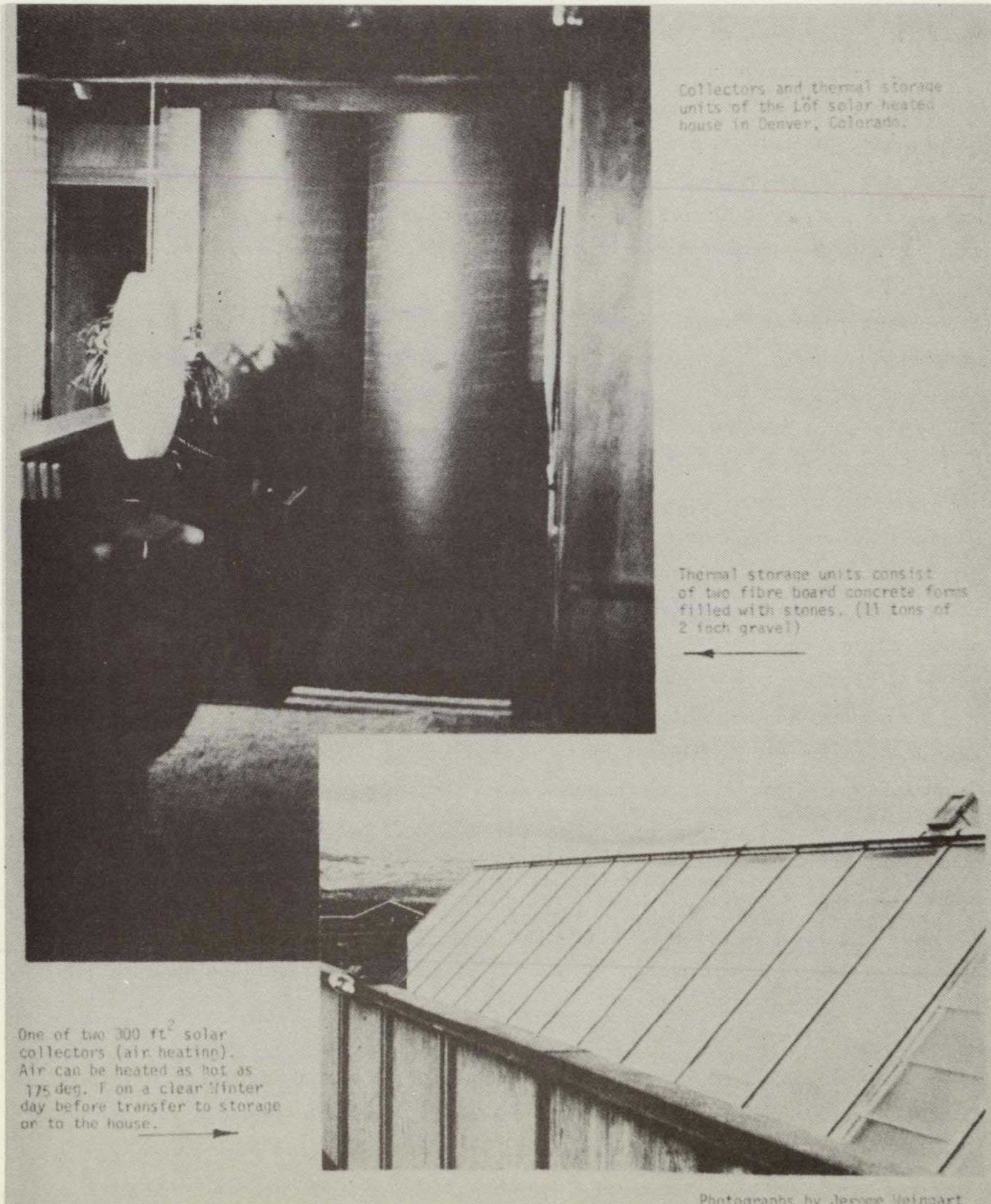



Figure 2-14. The Löf Solar Heated House – Denver, Colorado (1958)

Heat is transferred to the rock storage system, and cooled air is then recirculated through the rooftop collectors. This system supplies about 30% of the heating required for a typical winter, and virtually all of the hot water for a year. At today's prices the system in the Löf house would save a Denver resident \$150/yr on gas bills (1973 prices). If mass produced, it would sell for as much as \$1400 more than a conventional system; custom made installations would be even more expensive.

Among solar heated houses designed more recently is a demonstration project for Ms. A. N. Wilson, of the National Park Service. The 1400-ft$^2$ house in Shanghai, West Virginia, reflects a high level of energy conservation. The main solar array is a half water-half ethleneglycol solution heating collector 588 ft$^2$ in area, facing south at a 45-deg angle. Several storage tanks at different temperatures are used for thermal storage; this permits greater flexibility for the heating and cooling subsystems. Supplementary heat is provided by an oil-fired water heater. The house was designed by P. Richard Rittleman, an architect and mechanical engineer, and member of the NASA/NSF Solar Energy Panel.

Another recently designed building using solar heating and cooling is the new Massachusetts Audubon Society headquarters. The Arthur D. Little Company and Cambridge Seven Associates, Architects, collaborated on the design. While most constructed solar projects have been primarily of residential scale, this one is considerably larger, involving a solar collector of approximately 3500 ft$^2$. It is estimated that the building will supply between 65 and 75% of the total seasonal heating load, while a solar-driven lithium bromide absorption refrigeration unit will be used to service the building's 15-ton air-conditioning load.

Another solar project, which is definitely not in the mainstream of the U.S. construction industry but which deserves serious mention in any overview of solar homes, is the dome house built near Albuquerque, New Mexico, designed by Robert Reines, also a member of the NASA/NSF Solar Engery Panel. (Figure 2-15).

(Photo: Richard Caputo)

This dwelling system derives all of its energy needs from the sun and the wind. Wind driven generators provide all electrical energy needs, including space heating. Solar panels and an insulated hot water storage tank provide abundant hot water all year. Thermal and electrical storage is adequate to handle periods without sun or wind for up to several weeks (demonstrated during the Winter of 1972). Thick styrafoam insulation and an airlock entrance minimizes heat losses during the Winter.

This system was conceived, designed and built (with some help from his friends) by Robert Reines. It is located near Albuquerque, New Mexico and :epresents a serious committment to demonstrating the possibilities of ecosystemic design.

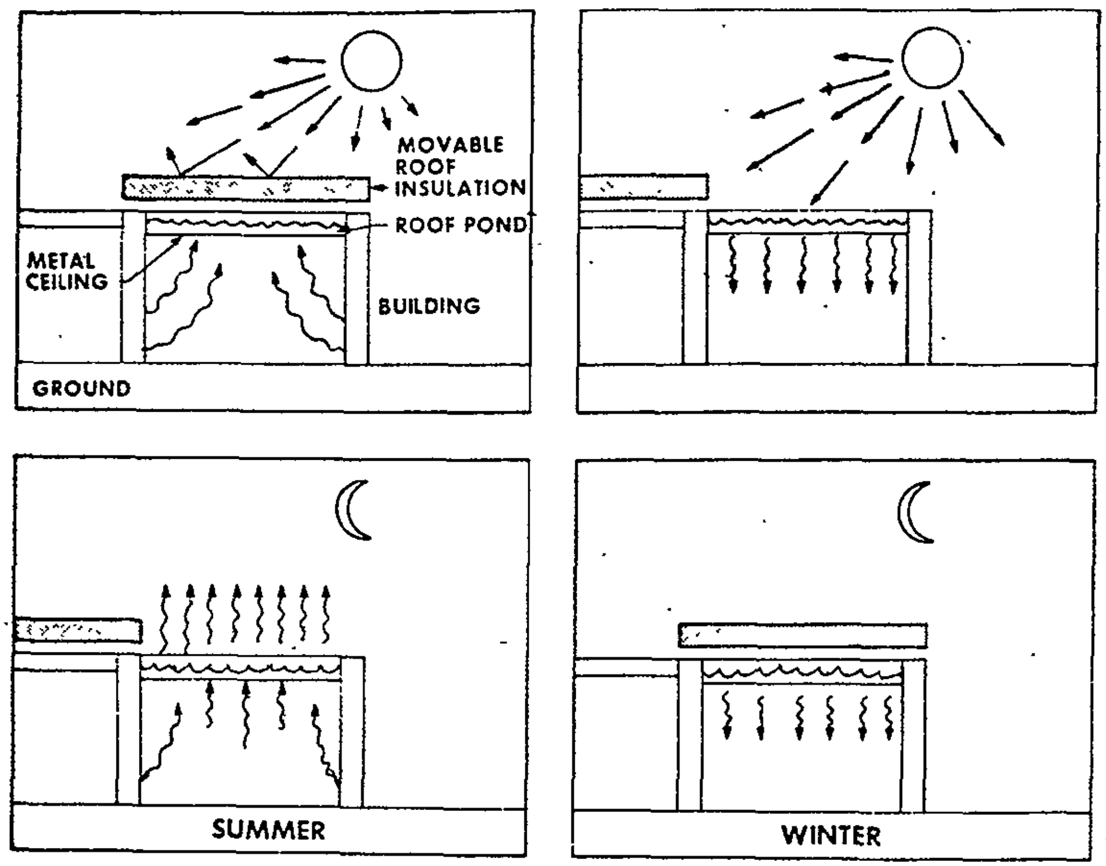
Source: New Energy Technologies for Buildings, 1975.

Figure 2-15. An Integrated Living System

Reines' prototype system consists of a highly insulated home structure with wind-generated electricity providing all the requirements for space heating, lighting, appliances, and other equipment. Three solar collectors and a large insulated hot-water storage tank provide abundant hot water all year. The Reines -designed community contains a number of buildings to house a small group of students and professionals from various fields. The prototype system, which represents a personal commitment on the part of Reines to an ecosystemic ethic, survived a rough winter without any failure of the subsystems. A simplified operating diagram (Figure 2-16) shows the system's basic elements.

This system demonstrates that a carefully designed and operated living system can provide comfort and amenities without the use of energy other than that supplied from its own wind and solar conversion elements. Although neither we nor Reines would propose that future U.S. communities entirely resemble this system in form, the concept of systemic design, with energy conservation as an implicit part of the design ethic, is applicable to the design and operation of more conventional structures and communities.

Only a few solar-operated air conditioning units have been assembled, and still fewer buildings have been constructed that have even partial solar air conditioning. Perhaps the approach to solar heating and cooling which is most akin to the direct use of natural energies exemplified by Mesa Verde is that developed by California chemist-engineer-inventor, Harold Hay. His approach is particularly well suited to the hot, dry climate of the Southwest, although it can also work elsewhere. The principle of operation is shown in Figure 2-17. The roof of a building consists of a metal ceiling, with a roof pond covered by a movable sheet of insulation. During the summer, the pond is cooled at night by nocturnal radiation, evaporation, and conduction to the atmosphere. In the day, the insulation, with a reflective upper surface, covers the pond, preventing solar energy from warming it; heat from the interior space is absorbed in the cool roof pond. During the winter, the procedure is reversed. In the day, the insulation is retracted and the roof pond is heated by the sun. At night, the pond is covered by the insulation, and the warm water in contact with the ceiling keeps the interior spaces warm through radiation and conduction/convection.




Source: Schoen, Hirshberg, and Weingart

Figure 2-17. A Naturally Air-Conditioned Building (Designer: Harold Hay)

A prototype home has been constructed in San Luis Obispo, California, to demonstrate that a relatively simple system such as this can provide most heating and cooling needs for one-story buildings, located between 35°N. and 35°S. latitudes, and most of the needs for two-story buildings in fairly mild climates in the southwest. Hay feels that the evaluation of the building will confirm his expectations that such a system will not add significantly to the first costs of homes built on a production basis.

The approach to solar air conditioning which is being more widely pursued at this time is to provide heat from solar collectors to ammonia or lithium bromide absorption refrigeration units similar to those which are the basis for residential and commercial gas air conditioning units, and to the gas refrigerator which used to be a common household appliance. Lithium bromide absorption systems can be driven by solar-generated heat at 180°F from a flat-plate collector, while ammonia absorption systems require heat in the 220°F range.

In addition to the absorption concept, considerable effort is currently being expended to develop higher temperature flat-plate collectors or low concentration (single-axis tracking parabolic) focusing collectors in order to create shaft horsepower. Rankine cycle engines could then be used to operate standard compression refrigeration units and to drive electrical generators.

As with water and space heating systems using solar energy, a supplementary heat source such as natural gas or fuel oil is required if economics of operation are to be optimized, since storage of thermal energy for long periods (over several days) is far more expensive than systems with supplemental energy sources. A simple conceptual diagram of a combined solar heating/cooling system is shown in Figure 2-18.

An experimental solar-cooled house has been constructed in Brisbane, Australia. The house was designed with a 750-ft$^2$ collector driving the 3-ton absorption unit. The system demonstrated that solar air conditioning could be achieved with a reasonable collector size, but detailed evaluation has awaited additional funding.

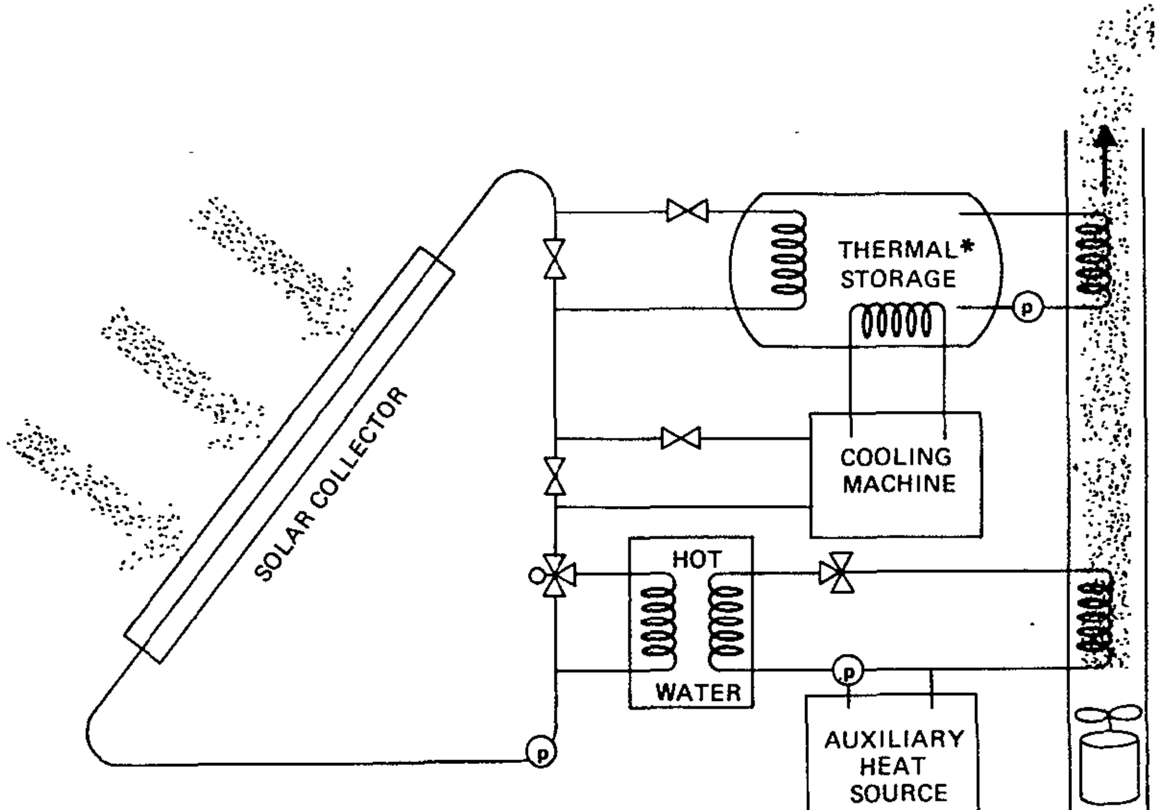



Figure 2-18. Combined Solar Heating and Cooling With Seasonal Storage

The use of photovoltaic thermal/electric collectors offers a number of potentially exciting possibilities for new energy systems. On a large scale, such a system might be used to provide a community of 40,000 persons with energy for all purposes. The implications of such systems upon the developing nations and their continuing efforts to raise their standards of living (as well as the increasing competition for the world's resources) could have a significant impact upon global economics and politics by the turn of the century.

One possible system which combines the thermal and electric conversion capabilities of a photovoltaic panel is shown in Figure 2-19. The system would provide heat directly for water and space heating; it would also provide electrical requirements for buildings and some forms of transportation (such as electric cars). If the system were connected to a utility grid, it could supply

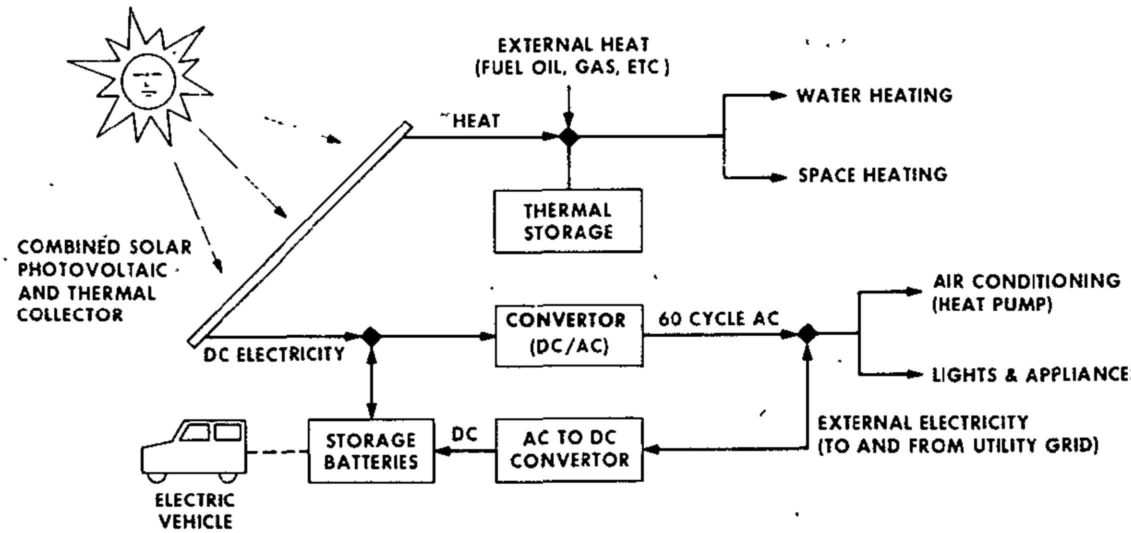



Figure 2-19. Combined Solar-Thermal Electric Conversion (a Conceptual Sketch of one Possible System)

energy to the grid during some parts of the day and draw electricity from the grid at night if supplemental energy was required. Such systems could act as load levelers for local electric utilities.

A modest but significant step in this direction -- Solar One, an experimental 1500 ft$^2$ building -- has been constructed at the University of Delaware under the direction of Professor Boer, Director of the Institute of Energy Conversion. It uses cadmium sulphide photovoltaic cells as solar collectors to generate electricity, and lead-acid batteries for storage. Direct current electricity is used for some loads (lights, stove, heating), while alternating current is used for other appliances (heat pump, fan motors, refrigerator). Thermal storage, together with a heat pump, maximizes the use of solar energy, and shifts the operating time of the heat pump into off-peak nighttime operation. Planned for the building are relays to control load switching between the solar system and the utility grid to provide load relief for power utilities during the hours of peak demand.

Because there are no commercial, mass-produced solar conversion elements presently on the market, the costs of owning and operating various types of solar energy systems are not yet well understood. For some of the simpler systems, costs have been estimated from experience with prototype heating and cooling systems, and from solar collector manufacturing experiences in Australia, Israel, and Florida. Most reasonable estimates indicate that solar water heating, space heating, and air conditioning would be competitive, on an annualized basis with many all-electric systems. For example, solar water heating and space heating could compete well with resistive electric heating at 1973 prices for electricity in most areas of the country. These solar systems generally cannot yet compete with gas or oil. But the rapid rise in prices for such fuels and the growing constraints on new natural gas hookups in many parts of the country are likely to make solar systems competitive in areas currently serviced by these fuels within the next one to ten years, depending on the locale.

Although the cost of photovoltaic spacecraft power systems is extremely high, the possibility for producing commercial analogs to such systems for terrestrial applications at reasonable costs seems a strong possibility. Recent research at the University of Delaware indicates that if the processes for mass production of reasonable efficient (5% or greater) thin film solar cells can be developed, the cost of electric energy delivered by systems incorporating such panels is likely to be competitive with central station-generated electricity within the coming decade. Whether or not this can be accomplished is a matter of considerable debate in the solar energy community.

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